Amplifying Waveguide Optical Isolator with an Integrated Electromagnet

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We have demonstrated an amplifying waveguide optical isolator with an integrated electromagnet. This provides a solution to the generally poor magnetic remanence of this type of isolator. The proof of principle is presented and optimization routes are discussed.

Introduction

An optical isolator is indispensable in an optical telecom link to protect semiconductor lasers from optical feedback. A planar, waveguide version of the optical isolator is highly desirable as it would greatly reduce the packaging cost – hence the overall cost – of a laser diode module, because it avoids the expensive alignment required with current commercial bulk isolators.

An integratable isolator configuration that is getting a lot of attention in recent years is the amplifying waveguide optical isolator [1]-[3]. The device basically is a semiconductor optical amplifier (SOA) with a transversally magnetized ferromagnetic film close to the guiding core. The magneto-optic (MO) Kerr effect causes a non-reciprocal shift of the complex effective index of the guided modes, implying that the modal loss is dependent on the propagation direction. Electrical biasing decreases the overall loss level in the device. The result is a device which, being transparent in one direction while providing loss in the opposite direction, is isolating. The main advantage of this isolator concept is that monolithic integration with a semiconductor laser is straightforward, as both components are essentially the same. Configurations operating in transverse magnetic (TM) polarization [1]-[3] and transverse electric (TE) polarization [2] have been demonstrated. One of the main issues for this kind of device is the magnetization of the ferromagnetic metal film. The very high aspect ratio of the length of the film to the width results in very low remanent magnetization of the film due to large demagnetizing fields. One of the solutions to this problem is to have a magnet integrated with the isolator. In this paper we demonstrate a TM-mode amplifying waveguide isolator with an integrated electromagnet. This magnet is a gold strip deposited along the longitudinal direction of the isolator in close vicinity to the ferromagnetic film, which in this configuration both acts as the source of the non-reciprocity and as the electrical contact for the SOA. Current flowing through the gold strip from one side of the cavity to the other generates a transverse magnetic field causing the MO Kerr effect.

Apart from the application as an optical isolator, this result is interesting in itself as it is now possible to modify the internal loss of an SOA dynamically and non-reciprocally.

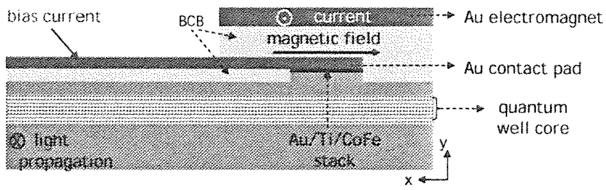

Figure 1: Schematic cross-section of the TM-mode amplifying waveguide isolator with integrated electromagnet.

Design and fabrication

The design of the amplifying waveguide optical isolator and the integrated electromagnet can be considered as two separate parts. The design of the isolator itself was extensively described in our previous work [3] hence we will limit ourselves here to a description of the component. The amplifying core is an AlGaInAs (λ_g = 1288nm) tensile strained (-1.6% strain) multiple quantum well structure. The ferromagnetic metal contact is a $Co_{50}Fe_{50}$ film. Proper design of the thickness of the top cladding layer and the two separate confinement heterostructure (SCH) layers gives the optimized theoretical performance: 62mA suffices to achieve transparency on a 2mm long isolator providing 10dB optical isolation [4], where the ridge width was set at 2μm.
A schematic cross-section of the amplifying waveguide optical isolator with integrated electromagnet is given in figure 1. The design parameters for the electromagnet are the width of the gold stripe and the distance between the electromagnet and the ferromagnetic metal film. Other parameters are the thickness of the gold stripe, which influences the current density in the electromagnet but not the strength of the magnetic field, and the variation of the generated magnetic field in the lateral direction (x-direction), which is of only minor importance if the stripe width is much larger than the width of the ferromagnetic film. The latter has to be the case for the isolator to ensure that the magnetic field is aligned along the lateral direction (x-direction). The partial differential equation describing the magnetic field problem was solved numerically. An electromagnet width of 5μm gives the best compromise between high magnetic field per unit of injected current and minimal variation of the magnetic field along the lateral direction. At this width the magnetic field is quasi-independent of the distance from the electromagnet. With the available lithography mask it was only possible to have an electromagnet gold stripe as wide as 30μm, resulting in a magnetic field that is a factor 5 lower than optimized. However, it is suitable for a proof-of-principle experiment.
For details on the fabrication of the isolator itself we refer to reference [3]. On top of the isolator bias contact a 30μm wide and 215nm thick gold stripe is deposited, serving as the electromagnet. Both gold stripes are separated by a 1μm thick benzocyclobutene (BCB) layer. Isolators with a cavity length of 1.3mm have been cleaved and mounted for characterization.

Characterization

An easy and fast characterization method for the amplifying waveguide optical isolator is to pump as-cleaved isolators above threshold and extract the emitted power as a function

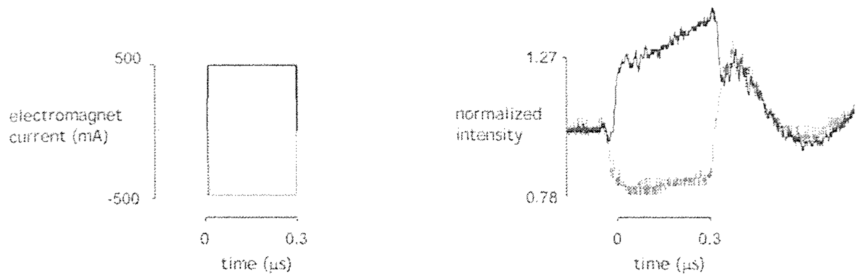

Figure 2: (left) Time evolution of the injected (pulsed) current in the electromagnet. (right) Corresponding (normalized) intensity emitted by the optical isolator at a bias current of 140mA (= above threshold).

of the applied lateral magnetic field – switching the magnetic field direction is equivalent to switching the light propagation direction. Because the material gain is clamped above threshold the non-reciprocal loss shift is independent of the isolator bias current and the optical isolation can be extracted from the ratio of forward to backward intensity – or equivalently the ratio of the intensity at magnetization in either lateral direction:

$$isolation[dB] = 2\frac{10}{ln10}\, ln(intensity\ ratio) \qquad (1)$$

This method is used throughout this paper; the integrated electromagnet is characterized by applying current to the gold strip while pumping the isolator above threshold. To avoid heating, the electromagnet is driven with pulsed current (pulse width $0.3\mu s$, duty cycle 3%). The chip temperature is controlled with a thermoelectric cooler at a value of 20°C. The isolator bias current is continuous wave (CW). The output signal is evaluated on a digital sampling oscilloscope. The measurement is done for both directions of the current flow in the electromagnet, corresponding to a magnetic field in either lateral direction. The right part of figure 2 shows the measured time evolution of the intensity. The corresponding pulsed current is plotted in the left part of figure 2, where negative current corresponds to reversed current flow direction. The intensity is normalized to compensate for variations in the fiber-to-chip coupling. At the on-set of the current pulse the emitted power rapidly increases or decreases, depending on the current flow direction. This is a clear proof of the on-set of the non-reciprocal loss shift. After the off-set of the pulse, the emitted power quickly becomes identical again in both cases and then slowly recovers from the heating of the device. The ratio of the intensity at "forward" to that at "backward" current injection equals 1.64, which for an isolator of 1.3mm cavity length corresponds to an isolation of 4.3dB.

We repeated the measurements for different values of the electromagnet current injection. In figure 3 the corresponding evolution of the optical isolation with injected (pulsed) current is plotted (bottom axis). For comparison the optical isolation as a function of the strength of an externally applied magnetic field is also given (top axis). Fitting both graphs shows that with a current injection of 500mA the achieved magnetic field is half the value needed to saturate the ferromagnetic film. The corresponding isolation (4.3dB) is 70% of the value at magnetic saturation. In conclusion, a very high current of 1.1A is

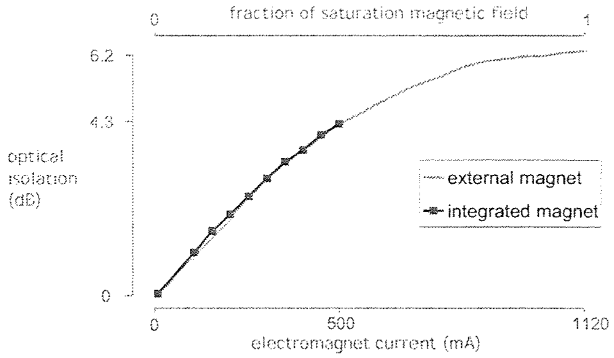

Figure 3: Evolution of the optical isolation with current in the electromagnet (bottom axis) and with externally applied magnetic field (top axis).

needed to achieve magnetic saturation with the fabricated electromagnet. However, decreasing the width of the gold strip to $5\mu m$ will decrease the required current by a factor of 5.

Conclusion

We have developed an optical isolator with an integrated electromagnet. While the demonstrated drive current is beyond the acceptable level, possibilities for major improvement have been identified. Further research is however required, as the electromagnet drive current should be lower than 50mA to limit its contribution to the overall power consumption of the amplifying waveguide optical isolator.

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